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Experimental results of 5-Gbps free-space coherent optical communications with adaptive optics[☆]

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ABSTRACT

In a free-space optical communication system with fiber optical components, the received signal beam must be coupled into a single-mode fiber (SMF) before being amplified and detected. The impacts analysis of tracking errors and wavefront distortion on SMF coupling show that under the condition of relatively strong turbulence, only the tracking errors compensation is not enough, and turbulence wavefront aberration is required to be corrected. Based on our previous study and design of SMF coupling system with a 137-element continuous surface deformable mirror AO unit, we perform an experiment of a 5-Gbps Free-space Coherent Optical Communication (FSCOC) system, in which the eye pattern and Bit-error Rate (BER) are displayed. The comparative results are shown that the influence of the atmospheric is fatal in FSCOC systems. The BER of coherent communication is under 10^{-6} with AO compensation, which drops significantly compared with the BER without AO correction.

1. Introduction

FREE-SPACE optical communication (FSOC), with high confidentiality and high code rate, is considered the only way to solve the bottleneck for achieving a high-speed broadband network of satellite–satellite, satellite–ground, and deep-space links in the future. While free-space RF communication limits the data rate to roughly 1 Gbps, FSOC will extend its capacity into nearly 100 Gbps for the future system by means of homodyne or heterodyne detection techniques. Those techniques transmit information by modulating the frequency or the phase of the signal beam and the signal is demodulated by coherent light systems. Such systems, as known as Free-space coherent optical communications (FSCOC), can improve the receiver sensitivity up to 20 dB compared with intensity modulation with direct detection (IM/DD). Besides, the use of coherent detection may allow a more efficient utilization of fiber bandwidth by increasing the spectral efficiency of WDM systems [1,2].

However, propagation through atmospheric turbulence seriously degrades the spatial coherence of the signal beam and limits the application of atmospheric optical communications especially in FSCOC systems on account of the high sensitivity to the wavefront phase [3]. The adaptive optics (AO), which is widely used in astronomy [4–6], is a promising way to compensate the weakness of FSCOC systems by real-time correction of the wavefront aberrations caused by turbulence.

The study of the FSCOC has been the subject of much theoretical and experimental work. Many existing researching works focused on the performance analysis of the FSCOC system based on spatial coherence techniques [7,8], which are mainly the theoretical analysis of the mixing efficiency and bit-error rate (BER) performance of the coherent detection. On the other hand, optical fiber communication, with fiber optical components such as transmitter and receiver modules, erbium-doped fiber amplifiers, and multiplexer units, has developed rapidly. The introduction of optical fiber receivers can greatly simplify the system structure and reduce the energy consumption. In such system, the received signal beam must be coupled into a single-mode fiber (SMF) before being amplified and detected. The topic involves theoretical and experimental research. Arimoto et al. described a method to increase the SMF coupling efficiency with a fast steering mirror [9]. However, it can only be used under weak turbulence. Weyrauch et al. studied a fiber coupling system for free-space optical communications based on an AO system without wavefront sensors [10]. It has a low bandwidth and cannot be applied to the real atmospheric turbulence link.

In our previous work, we presented a SMF system with the aid of the 137-element continuous surface deformable mirror AO technique and obtained SMF coupling efficiency of 46.1% [11]. In this paper, we analyze the influence of atmospheric turbulence on the SMF coupling

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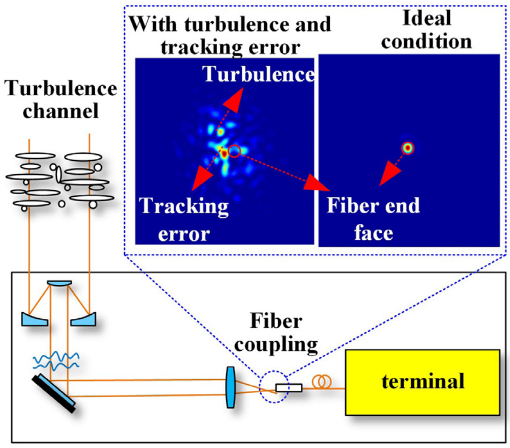

Fig. 1. Schematic diagram of fiber coupling over turbulence channel.

efficiency more specifically and set up a 5-Gbps FSCOC system with a 137-element AO unit. Finally, the fluctuation of the receiving power, eye-pattern, and bit error rate (BER) are acquired.

2. influence of turbulence on SMF

The schematic diagram of atmospheric optical communications with fiber coupling is illustrated in Fig. 1. A signal beam propagates through the atmospheric turbulence channel before entering the receiving telescope. The light beam is focused on the end face of a single mode fiber with a coupling lens. In an ideal condition, the distribution of the signal beam in the focal plane is an Airy pattern and most of the light energy is concentrated on the optical fiber end face. However, in an atmospheric communication system, the process of fiber coupling faces two problems. The first one is the wavefront distortion mostly caused by turbulence. The far-field beam quality degrades because of turbulence. The second one is tracking errors caused by turbulence and platform jitter. In some cases, the tracking errors could be considered as low-order wavefront distortion which is known as the tilt.

The coupling efficiency is defined as the ratio of the average energy coupled into the SMF to the average energy in the focus plane, and it is given by [12]

$$\eta_f = \frac{\langle P_f \rangle}{\langle P_i \rangle} = \frac{\left\langle \left| \int_S E(x,y) F(x,y)\, dx dy \right|^2 \right\rangle}{\left\langle \int_S |E(x,y)|^2 dx dy \times \int_s |F(x,y)|^2 dx dy \right\rangle}, \tag{1}$$

where $E(x, y)$ is the distribution of the signal beam on the focal plane, and $F(x, y)$ is the normalized fiber-mode profile when the normalized frequency V of the SMF is in the range of $1.9 \leq V \leq 2.4$. It can be approximated by the Gaussian distribution

$$F(x,y) = \sqrt{\frac{2}{\pi w_0} \exp\left(-\frac{x^2+y^2}{w_0^2}\right)}, \tag{2}$$

where ω_0 represents the mode field radius of the fiber core. When the fiber coupling system is only influenced by tracking errors, the coupling efficiency with an offset bias ρ between the center of the focused beam and the nominal axis of the fiber core can be expressed as [13]

$$\eta = \left| \int \frac{2\sqrt{2}}{w_0} J_1\left(\frac{kDr}{2f}\right) \exp\left(-\frac{r^2+\rho^2}{w_0^2}\right) J_0\left(\frac{2r\rho}{w_0^2}\right) dr \right|^2, \tag{3}$$

where $J(\cdot)$ is the Bessel function of the first kind of order zero. The parameter f is the focal length of the coupling lens and the parameter D is the diameter of the signal beam. In an optical communication system, we usually use angular errors to describe the tracking errors. The angular errors of the signal beam are known as

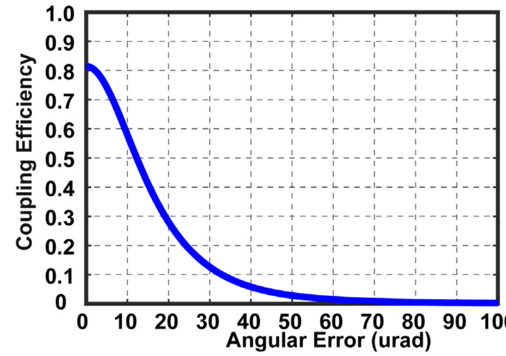

Fig. 2. Fiber coupling efficiency as a function of beam angular error.

$$\theta = \frac{\rho}{f}. \tag{4}$$

Fig. 2 shows the fiber coupling efficiency as a function of beam angular errors. The parameters of the system are given by $\lambda = 1550$ nm, $\omega_0 = 5$ μm, and $D/f = 0.23$. The result shows that tracking errors has a huge impact on coupling efficiency. When the angular error is $\theta \geq 40$ μrad, the coupling efficiency is under 10%. In order to obtain a higher rate of signal to noise, the tracking errors need to be reduced to under $\theta \geq 15$ μrad.

As it is much more convenient to evaluate the signal beam wavefront distribution before focusing on the fiber, we apply the backpropagating formalism to fiber mode $F'(x, y)$ and the incidence light distribution $E'(x, y)$. The coupling efficiency then is as follows [12]

$$\eta_f = \frac{\left\langle \left| \int_S E'(x,y) F'(x,y)\, dx dy \right|^2 \right\rangle}{\left\langle \int_S |E'(x,y)|^2 dx dy \times \int_s |F'(x,y)|^2 dx dy \right\rangle}. \tag{5}$$

Considering a plane signal wave influenced by the atmospheric turbulence, $E'(x, y)$ is given by

$$E'(x,y) = P(x,y) \exp[j2\pi\varphi(x,y)], \tag{6}$$

where $P(x, y)$ is the amplitude distribution of the signal beam and $\varphi(x, y)$ represents the phase distortion caused by turbulence. The backpropagated fiber mode $F'(x, y)$ can be expressed as [14]

$$F'(x,y) = \frac{\sqrt{2\pi} w_0}{\lambda f} \exp\left[-\left(\frac{\pi w_0}{\lambda f}\right)^2 (x^2+y^2)\right]. \tag{7}$$

According to Eqs. (5)–(7), the phase distortion can greatly influence the coupling efficiency. Fig. 3 shows the SMF coupling efficiency as function of wavefront phase root-mean-square (RMS). When the wavefront phase $RMS > 0.3\lambda$, the average coupling efficiency is 10% or even smaller.

The above analysis shows that both wavefront distortion and tracking errors have tremendous effect on SMF coupling efficiency and limit the application of free-space optical communications. Highly accurate tracking and wavefront distortion compensation are the key techniques for such communication systems. In our previous work [11], we point out that adopting the AO unit is a feasible way to solve those problems and analyze the different effectiveness of coupling efficiency with compensation by AO unit. Under the condition of relatively strong turbulence, only making the tracking errors compensation is not enough, and correction of turbulence wavefront aberration is required.

3. Experimental analysis of 5-Gbps FSCOC

In order to verify the effectiveness of the AO technology applied to the FSCOC system, we designed a FSCOC experimental system with